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Nutrient Interactions at the Sediment-Water Interface of Tile-Fed Agricultural Drainage Ditches

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Abstract. *Although a substantial number of studies have discussed nutrient transport and dynamics in pristine streams, little consideration has been given to nutrient transport processes in managed ditch environments. The study was conducted in three drainage ditches in northwest Indiana to: (1) assess equilibrium between sediments and water column P (2) evaluate spatial and seasonal variations in nutrient dynamics; (3) determine if differences existed in nutrient retention capacity between sediments collected upstream and downstream of tile drains. Equilibrium P Concentrations (EPC_0) varied between 0.05 and 6.2 mg/L. When sediment EPC_0 concentrations were compared to ditch water P concentrations, there was no particular pattern in the interactions of sediments with water at all three sites. Easily exchangeable P varied between 1.39 and 5.98 mg kg^{-1} sediment and the ability of sediments to buffer water column P as indicated by PSI values ranged from 6.5 to 15.2. These data were consistent with reported values by previous studies in drainage ditches of the area. Sampling location respective to tile drains did not have any effect on sediment behavior during the study. The results of this study indicated that these drainage ditches were very dynamic in adsorbing or desorbing nutrients into the water column. This study suggested that nutrient uptake by benthic sediments in drainage ditches is not always efficient, therefore proper management should be* *implemented to optimize for nutrient removal from the water column while maintaining adequate drainage.*

Keywords. *Sediments; EPC_0; nutrient dynamics; sediment interactions; drainage ditches.*

Introduction

Drainage ditches serve as waterways that collect water through surface runoff and sub-surface tile drains from agricultural fields and efficiently move the water to downstream water bodies (Sharpley et al., 2007). Of all the components that affect nutrient dynamics and transport in aquatic ecosystems, benthic sediments are probably the most influential determinant of the ability of the system to process and sustain nutrient loads (Klotz, 1985; Haggard et al., 1999). Sediments play an active role in nutrient uptake and may actively control nutrient concentrations in the overlying water column (Haggard et al., 2004; Smith et al, 2005).

Nutrients undergo many different processes once they enter aquatic environments (Meyer et al., 1988; Dodds et al., 2002; Strock et al., 2007). They may cycle from dissolved form to particulate form and back to dissolved form (Haggard et al., 2004). During cycling of nutrients, benthic sediments are constantly interacting with the overlying water column. Previous studies have quantified these interactions using several indices such as exchangeable P (Ex-P), exchangeable N (Ex-N), P sorption index (PSI), and equilibrium phosphorus concentration (EPC_0) (Haggard et al, 2004; Popova et al., 2006; Chaubey et al., 2007). Ex-P and Ex-N provide valuable information on the amount of nutrients that are loosely sorbed to benthic sediments (Haggard et al, 2004) and that can easily be released into the water column (Chaubey et al., 2007).

During the exchange reactions the ability of benthic sediment to adsorb P is measured by P sorption index (PSI) (Bache and Williams, 1971; Klotz, 1988; Chaubey et al., 2007). Klotz (1985) reported that a high PSI value indicates a high ability of sediments to buffer nutrients loads in streams. PSI is unitless and is proportionally related to temperature and particles size (Klotz, 1985; Popova, 2000).

While PSI describes the ability of benthic sediments to influence the water column P concentrations by adsorption (Bache and Williams, 1971), EPC_0 describes the source-sink relationship between ditch sediments and water column P concentrations (Smith et al., 2006a). EPC_0 is the concentration of water column P at which net P exchange rate between benthic sediments and water is zero (Klotz, 1988; Haggard et al, 2004; Chaubey et al., 2007). When water column P concentrations are greater than sediment EPC_0, sediments act as a sink and theoretically remove P from the water column, but sediments act as a source and theoretically release P into the water column when water column P concentrations are less than sediment EPC_0 (Meyer, 1979; House et al., 1995; Chaubey et al., 2007). EPC_0 is positively correlated to pH (Popova, 2000) and sediment specific surface area (Haggard et al., 1999; Smith et al., 2005). EPC_0 values have been reported in Northeast Indiana ditches to range between near 0 to 0.11 mg L^{-1} (Smith et al., 2005; Smith et al., 2006b).

Even though previous studies have reported that headwater streams efficiently transport nutrients (Alexander et al., 2007), the transport processes in drainage ditches are not well understood. Furthermore, little attention has been given to the effects of tile drains inputs on the transport of nutrients and their interaction with benthic sediments in managed ditch environments. Understanding the dynamics between the water column and sediments collected upstream and downstream of tile drains is needed to determine if the ditch ecosystem acts as a sink or a source of dissolved nutrients. This information is fundamental in anticipating specific areas in drainage ditches to be treated with BMPs for water quality protection.

The overall goal of this study was to determine if benthic sediments in these ditches act as a sink or a source for nutrients with respect to tile location. The specific objectives were to: (1) assess equilibrium between sediments and water column P in three Indiana's drainage ditches; (2) evaluate spatial and seasonal variations in nutrient dynamics in these ditches; (3)

determine if differences existed in nutrient retention capacity between sediments collected upstream and sediments collected downstream from tile drains.

Study Site Description

This study was conducted in three different ditches in northwest Indiana: J.B. Foltz ditch near Reynolds, Box and Marshall ditches near West Lafayette. The J.B. Foltz ditch is one of the headwater ditches of Hoagland watershed located in Benton, Jasper and White Counties about 48.3 km from the Purdue University campus (Figure 1). The ditch drains about 7.7 km^2 into Minch ditch which, together with Hoagland ditch, discharge into the Tippecanoe River. The study portion of the ditch, which drains about 1.5 km^2, is mostly vegetated and has not been dredged for many years. In summer the riparian area of the ditch is rapidly invaded by tall grass including a variety of big bluestem (*Andropogon gerardii*), indian grass (*Sorghastrum*), and switchgrass (*Panicum virgatum*) of an average height of 1.3 m. The ditch flows in a relatively straight line with a sharp bend on the study reach. The area drained by the ditch is highly agricultural and dominated by rock, sand and clay with very poorly (71%) to poorly drained (18%) soils and an average slope less than 0.6 % with a total relief about 46 m reported for the entire watershed (Naz et al., 2008). Primary soils in the contributing area of the study reach are Gilford sandy loam (coarse-loamy, mixed, superactive, mesic Typic Endoaquolls) and Rensselaer loam (fine-loamy, mixed, superactive, mesic Typic Argiaquolls) with elevation ranging from 233 to 250 m. Corn and soybean are predominant land use (93%) and the remaining land use (7%) is a combination of low density residential area, pasture and grass.

The Box ditch and the Marshall ditch are located approximately 11.3 km northwest from Purdue University in Little Pine Creek-McFarland/Otterbein watershed. The watershed is situated in northwest Tippecanoe County, Indiana (Figure 1) and covers 53.3 km^2. Marshall ditch and Box ditch are both headwaters and drain approximately 8.0 km^2 each of agricultural and livestock (90%) and low density residential area (10%) land uses into Little Pine Creek. Corn and soybean are most cultivated crops in the watershed. The portion of Box ditch used for the study reach drains approximately 0.3 km^2 with pasture and small trees dominate in the riparian area. Similarly, Marshall ditch study area drains about 0.2 km^2 periodically irrigated with effluent from a swine lagoon. Major soils in the contributing area in both ditches are Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls) and Toronto silt loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls) with 0-2% slope and elevation ranging from 218 to 223 m.

Materials and Methods

Field Techniques

Sediments were collected approximately 5 m upstream and 5 m downstream of selected tile drain outlet at a single point every three months for a year (July 2007-September 2007, October 2007-December 2007, January 2008-March 2008, April 2008-June 2008, and July 2008-September 2008; total n = 4 per sampling station). Sampling locations were chosen based on the distance between two given tile drain outlets. Given the constraints of at least 200 m distance between two outlets, four outlets were selected on Box ditch, five on J.B. Foltz ditch, and three on Marshall ditch (Table 1). The J.B. Foltz ditch had eight sampling stations every three months involving all five tile drain outlets and starting five m downstream the most upstream tile (Table 2).

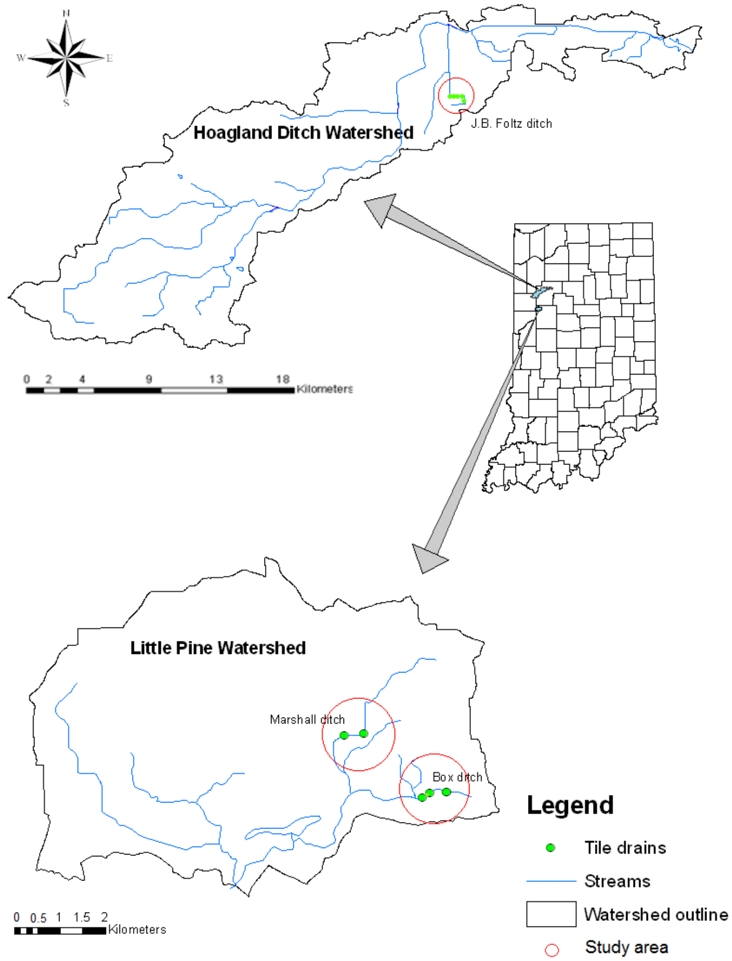

Figure 1 Study Sites in Hoagland and Little Pine Watersheds

Table 1. Study Sites Showing Global Positioning System Coordinates of Selected Tile Drain Outlets and Respective Distances from the Most Upstream Tile Outlet.

Ditch	Tile	Diameter (cm)	Longitude	Latitude	Distance (m)
J.B. Foltz ditch, Reynolds, IN	1	16.5	W 86º 55.215	N 40º 46.868	0
	2	15.2	W 86º 55.295	N 40º 47.020	385
	3	20.3	W 86º 55.464	N 40º 47.017	621
	4	20.3	W 86º 55.608	N 40º 47.010	826
	5	20.3	W 86º 55.756	N 40º 47.006	1036
Box ditch, West Lafayette, IN	1[a]	186	W 86º 59.899	N 40º 29.659	0
	2	22.9	W 86º 59.897	N 40º 29.658	7.32
	3	22.9	W 87º 00.114	N 40º 29.668	336
	4	22.9	W 87º 00.269	N 40º 29.593	456
Marshall ditch, West Lafayette, IN	1	35.6	W 87º 01.186	N 40º 30.351	0
	2[b]	30.5	W 87º 01.506	N 40º 30.336	431

1[a] : small ditch entering the main ditch through a pipe
2[b] : conventional weir flow control structure with circular spillway

Table 2 Location of Sampling Stations for Sediment Extraction in Respective Ditches.

Ditch	UT1	DT1	UT2	DT2	UT3	DT3	UT4	DT4	UT5	DT5
J.B. Foltz	–	SS	SS	SS	SS	SS	SS	SS	SS	
Box	SS	combined		SS	SS	SS	SS	–	–	–
Marshall	SS	SS	SS	–	–	–	–	–	–	–
UT = upstream of tile outlet; DT= downstream of tile outlet; SS = sampling station; 1,2,3,4,5 = tile outlets										

The J.B. Foltz ditch had eight sampling stations every three months involving all five tile drain outlets and starting five m downstream the most upstream tile (Table 2). The Marshall ditch and the Box ditch had three and five sediment sampling stations, respectively (Table 2). Tile outlet 1 and tile outlet 2 were considered as a single tile drain outlet on Box ditch due to their close proximity.

Sediment samples were collected by approaching the sampling station from downstream to avoid disturbance. Sediments were gently removed from the top 2-8 cm of the ditch bed with a trowel and placed into plastic ziploc freezer bags. About 2L of unfiltered and 60 mL of filtered background ditch water in nalgene bottles were also collected from the center of the ditch at the sampling station. During each sampling event, conductivity, dissolved oxygen, salinity, and temperature were measured in the water column at the sampling point using conductivity meter 115A plus (YSI Model 85 10' cable) and pH was measured using Chek-Mite pH-15 Sensor. Sediment and water samples were stored in the dark on ice until transported to the laboratory. Sediment extractions were performed immediately after returning to the laboratory.

Laboratory Techniques and Calculations

Collected sediments were extracted for Ex-P, Ex-N, PSI, and sediment EPC_0 using methods outlined by Chaubey et al. (2007). EPC_0 was measured by spiking 5 separate 100 mL filtered ditch water samples with 0, 5, 10, 20 and 50 mg L^{-1} of additional PO_4-P. Each spiked solution was added to approximately 25 g of wet sediment in a 250 mL Erlenmeyer flask. Triplicate analyses were performed in all cases. The flasks were shaken at 120 oscillations min^{-1} for 1 hr with an automatic shaker. At 15 min interval the flasks were vigorously shaken manually and replaced on the shaker. At the end of the hour, the flasks were removed from the shaker and the contents were allowed to settle for at least 45 min. The supernatant of each flask was filtered manually using a 30 mL HDPE syringe and a 0.45μm nylon filter membrane into a pre-labeled 60 mL nalgene bottle. These aliquots were preserved at pH < 2 with sulfuric acid and stored at 4ºC until analyzed for dissolved P using inductively coupled plasma-optical emission spectrometry (ICP-OES). The remaining sediments were transferred to tared and pre-labeled aluminum pans and dried at 80°C for 48 h in an oven (VWR Model 1370 GM) to determine sediment dry mass. EPC_0 was estimated as the x-intercept of the regression line when the amount of P sorbed is plotted versus initial dissolved P concentrations used for P sorption isotherms (Klotz, 1988).

Phosphorus sorption index (PSI) was determined by spiking 100 mL of filtered ditch water with additional 2 mg/L of PO_4-P (Bache and Williams, 1971). This solution was added to approximately 25 g of wet sediment in a 250 mL Erlenmeyer flask. Similar extraction procedures to EPC_0 determination were performed and the aliquots were analyzed by inductively coupled plasma-optical emission spectrometry (ICP-OES). A triplicate was prepared for each case and PSI was calculated using the following equation (Chaubey et al., 2007):

$$PSI = \frac{X_P}{\log C_P} \tag{1}$$

where X_P is the amount of phosphate adsorbed (mg kg^{-1} of dry sediments) from initial concentration of 2 mg L^{-1} and C_P is the final nutrient concentration of phosphate (mg L^{-1}) in solution after one hour.

Ex-P was determined by adding 100 mL of 1M of $MgCl_2$ (Ruttenburg, 1992) to approximately 25 g of wet sediment in a 250 mL Erlenmeyer flask. The samples were prepared in triplicate and similar extraction steps to EPC_0 determination were followed. The aliquots were analyzed by ICP-OES and the exchangeable P concentration was calculated as mg of P per kg of dry sediment (Chaubey et al., 2007):

$$Ex - P = \frac{\left([\mathrm{P}\ (\mu g\ \mathrm{nutrient})/\mathrm{L}\right) * 0.1\mathrm{L}}{\text{dry sediment mass}} \tag{2}$$

Ex-N was estimated by adding 100 mL of 2M of KCl (Keeney and Nelson, 1982) to approximately 25 g of wet sediment in a 250 mL Erlenmeyer flask. The samples were prepared in triplicate and similar extraction steps to EPC_0 determination were followed. The aliquots were analyzed for ammonium by the reaction of alkaline phenate with hypochlorite and sodium nitroprusside (indophenol blue) method (Analyzer AQ2 EPA-103-A) and the exchangeable N concentration was estimated as mg of N per kg of dry sediment (Chaubey et al., 2007):

$$Ex - N = \frac{\left([\mathrm{N}](\ \mu\mathrm{g\ nutrient})/\mathrm{L}\right) * 0.1\mathrm{L}}{\text{dry sediment mass}} \tag{3}$$

Statistical Analysis

A two-factor ANOVA was used to determine in means of EPC_0, Ex-P, PSI, and Ex-N concentrations (1) site effects in a given season; (2) season effects within a given site. A three-way ANOVA was used to (1) compare mean differences between sediment EPC_0 and water column P concentrations; (2) evaluate differences in mean between sediments collected upstream and downstream from tile drains for EPC_0, Ex-P, PSI, and Ex-N concentrations among and across seasons. All variables were log transformed to meet normality requirements and a significance level $\alpha = 0.10$ was used. The General Linear Model procedure (proc GLM) in the Statistical Analysis System, version 9.1 (SAS, 2003) was used for all analyses.

Results and Discussion

Water Column Chemical Characteristics

Mean physico-chemical characteristics of ditch water column recorded during each sampling event for the three ditches are shown in Table 3. The pH varied between 7.1 and 9.2, but did not fluctuate drastically across sampling events and sites. This was comparable to the range of 6.5-9.0 published by Indian Administrative Code (IAC 2, 2008). Salinity was also consistent across sampling events and sites, ranging from 0.1-0.4 g L^{-1}. DO and temperature were inversely correlated in these ditches. In summer months, the warmer water has less ability to hold dissolved gases (Water on the web, 2009). The temperature in theses ecosystems corresponded to the seasonal temperature fluctuations in natural waters and did not show any abnormal temperature changes (IAC 2, 2008). Even though conductivity recorded across sites and sampling events was highly variable, the lowest conductivity values were observed during winter months and the highest conductivity values were measured in summer months.

Table 3. Mean Water Column Physico-Chemical Characteristics Recorded during Sediment Sampling for Extraction at the three Sites.

Season	Ditch	pH	Salinity ($g\ kg^{-1}$)	D. O. ($mg\ L^{-1}$)	Specific Cond. (µs)	Temp (ºC)
Jul-Sep						
	Box	7.7	0.3	3.6	509	19.0
	J.B. Foltz	8.1	0.3	5.9	537	23.8
	Marshall	8.0	0.4	4.6	664	14.8
Oct-Dec						
	Box	8.0	0.3	8.5	325	3.82
	J.B. Foltz	7.9	0.3	8.9	346	3.03
	Marshall	7.9	0.2	5.6	385	12.7
Jan-Mar						
	Box	7.9	0.3	6.7	329	1.10
	J.B. Foltz	7.8	0.3	5.5	343	6.69
	Marshall	7.3	0.3	15	324	1.57
Apr-Jun						
	Box	8.2	0.3	3.8	423	11.1
	J.B. Foltz	7.7	0.2	2.1	462	20.2
	Marshall	8.0	0.3	4.4	426	8.37

Sediment Extractions

Average EPC_0 varied between 0.05 and 0.2 mg L^{-1} in Box ditch, 0.03 and 6.2 mg L^{-1} in J.B. Foltz ditch, and 0.05 and 0.09 mg L^{-1} in Marshall ditch (Table 4). While the values in the Box and the Marshall ditches were consistent with data published in Indiana drainage ditches, the upper limit of EPC_0 values in J.B. Foltz ditch were much larger than the reported range of 0.02 to 0.11 mg L^{-1} (Smith et al., 2005; Smith et al., 2006b). This high value in J.B. Foltz ditch was the results of high EPC_0 measurements at tile outlet 1 on the study reach. The high EPC_0 at this location can be explained by the fact that two additional tile outlets were installed within 10 cm from the original tile outlet for experimental purposes by another group of researchers. The presence of these three tile outlets at the same location can increase the P losses to the ditch.

Intra-seasonal comparisons between sites for EPC_0 shown in Table 4 resulted in no significant differences between Marshall ditch and J.B. Foltz ditch. Box ditch EPC_0 was significantly lower than the observed EPC_0 in the other two ditches during the summer (July - September; $p < 0.01$). EPC_0 in Box ditch was significantly greater than the observed EPC_0 in the other two ditches throughout the rest of the year ($p < 0.02$). However, the standard deviation was relatively greater for Box ditch EPC_0 during the winter (January-March; Table 4).

Table 4. Estimated Mean and Standard Deviation of EPC_0, Ex−P, PSI and Ex-N at all Sites

during the Study Period.

	EPC_0 (mg P L^{-1} water)		Ex-P (mg P Kg^{-1})		PSI		Ex-N (mg N Kg^{-1})	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Jul - Sep								
Box	0.05	0.01	1.51	0.38	8.99	0.71	231	363
J.B. Foltz	6.20	9.33	2.34	0.77	9.33	1.73	826	1196
Marshall	0.09	0.01	1.51	0.07	7.90	0.79	70.1	38.6
Oct- Dec								
Box	0.20	0.08	5.98	1.51	9.61	3.10	20.2	9.67
J.B. Foltz	0.04	0.01	3.16	1.69	11.4	1.92	439	232
Marshall	0.08	0.03	1.85	0.21	7.22	1.54	138	147
Jan - Mar								
Box	0.20	0.16	5.38	1.48	8.22	0.61	88.6	128
J.B. Foltz	0.03	0.01	1.98	0.86	15.2	3.84	812	1284
Marshall	0.05	0.01	1.49	1.05	6.45	0.88	22.1	12.4
Apr- Jun								
Box	0.11	0.03	1.81	0.42	7.65	0.64	33.7	24.8
Foltz	0.08	0.06	2.09	1.13	8.90	3.04	215	198
Marshall	0.05	0.00	1.39	0.46	7.38	0.79	104	122

Inter-seasonal comparisons within a given site indicated that EPC_0 in Box ditch during the summer (Jul-Sept) was lower than EPC_0 of the other quarterly sampling periods ($p < 0.0001$). However, there were no significant differences between EPC_0 values of the quarterly sampling periods in J.B. Foltz ditch. Inter-seasonal comparisons in Marshall ditch indicated that Jul-Sept and Oct-Dec EPC_0 values were significantly greater than EPC_0 values for the Jan-Mar and Apr-Jun periods ($p < 0.02$).

Inter-seasonal comparisons between sediment EPC_0 and background P concentrations indicated that sediments in Box ditch acted as a source from October to June and as a sink between July and September (Figure 2; $p < 0.04$). Contrarily, sediments in J.B. Foltz ditch were absorbing P from the water column from October to June (Figure 2) but comparisons between water column P concentrations and sediment EPC_0 were significant only when sediments acted as temporary sink of P during Jan-Mar and as temporary source during Jul-Sept ($p < 0.01$). In Marshall ditch sediments acted as a P sink during cold months of the year (Oct-Mar) and as a P source during warm months (Figure 2).

Comparisons between mean sediment EPC_0 and mean background P concentrations showed no significant spatial and seasonal variation for all data across sites and seasons. Similarly, comparisons between mean sediment EPC_0 and mean background P concentrations within a site showed no significant difference across seasons. Comparisons of EPC_0 between upstream and downstream of tile drain resulted in no significant differences in mean EPC_0 between the two sampling locations, i.e. upstream and downstream of tile drains.

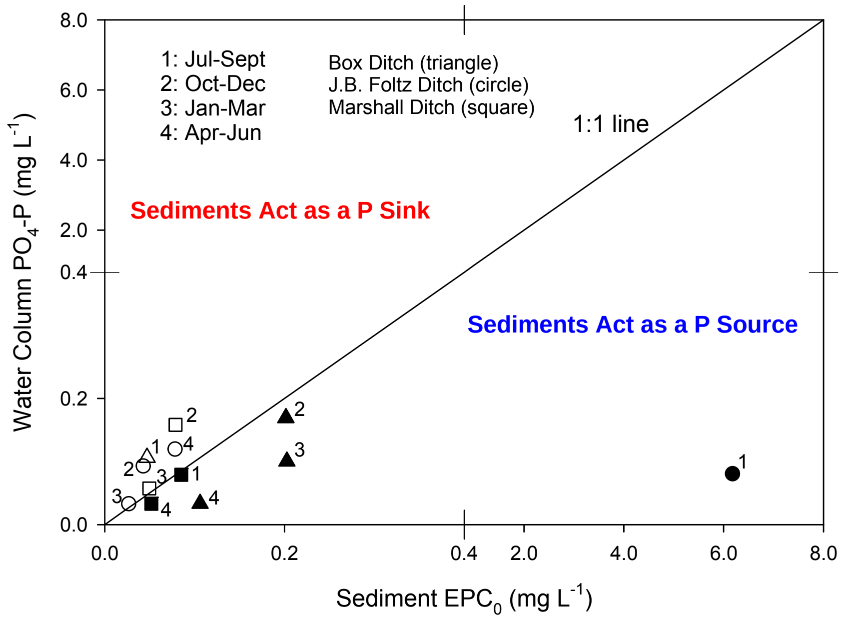

Figure 2 Comparison of Sediment EPC_0 and Water Column PO_4-P Concentrations Showing that the Ditch Sediments acted as a Sink or a Source of P to overlying Water Column.

Exchangeable P ranged from 1.51 to 5.98 mg kg^{-1} in Box Ditch, from 1.39 to 1.85 mg kg^{-1} in Marshall ditch, and from 1.98 to 3.16 mg kg^{-1} in Foltz ditch (Table 6). These data were consistent with the range of 0.5 to 9.35 mg kg^{-1} Ex−P concentration reported in the area drainage ditches (Smith et al., 2005; Smith et al., 2006b), but did not appear to decrease with increase in drainage area (Smith et al., 2005).When using Ex-P for comparisons, it should only be used for relative comparisons among sites because Ex-P is a very conservative estimate of loosely bound P (Chaubey et al., 2007).

Average Ex-P was generally higher in Box ditch (3.67 mg P kg^{-1}), followed by J.B. Foltz ditch (2.39 mg P kg^{-1}) and Marshall ditch (1.56 mg P kg^{-1}; $p < 0.004$). When season effects were tested on each site, results showed that Box ditch Oct-Dec and Jan-Mar Ex-P was significantly greater than Jul-Sept and Apr-Jun Ex-P ($p < 0.05$). In contrast, seasons did not affect significantly Ex-P in J.B. Foltz ditch. In Marshall ditch Jul-Sept Ex-P was significantly lower than Ex-P values observed between October and December ($p < 0.001$). In addition, Apr-Jun Ex-P in this ditch was significantly lower than Ex-P during Jan-Mar ($p < 0.0001$). Overall, mean Ex-P values were greater during October through December at all three sites ($p < 0.001$). This can be explained by lower biological activity during the cooler months, which reduced the biological demand for P from both sediment and water. Comparisons of Ex-P respective to sampling location (upstream and downstream of tile drain) among and across seasons did not indicate any significant difference at all sites.

Mean PSI values in this study ranged from 7.7 to 9.6 in Box ditch, from 8.9 to 15.2 in J.B. Foltz ditch, and from 6.5 to 7.9 in Marshall ditch (Table 6). These PSI values were comparable to the range of 2.7 to 13.8 published on Indiana drainage ditches (Smith et al., 2006b). Inter-site within a given season comparisons showed that sediment sorption ability of P in J.B. Foltz ditch was higher than PSI in the other two ditches for all seasons ($p < 0.09$). During

Jan-Mar, Marshall ditch PSI was significantly lower than PSI in Box ditch ($p < 0.0001$). Inter-seasonal comparisons of PSI within a ditch resulted in significant variations only in Box ditch where Jul-Sept, Oct-Dec and Jan-Mar PSI were significantly greater than Apr-Jun PSI ($p < 0.008$). The two-factor ANOVA used to determine differences between upstream and downstream of tile drain mean PSI among and across seasons within a ditch did not show any variation.

Mean Ex-N varied between 20 and 231 mg kg^{-1} in Box ditch, between 215 and 826 mg kg^{-1} in J.B. Foltz ditch, and between 22 and 138 mg kg^{-1} in Marshall ditch. Inter-site comparisons showed that Ex-N in J.B. Foltz ditch was greater than Ex-N in the other two ditches ($p < 0.06$). Season effects for each ditch indicated that Ex-N concentrations in Box ditch during Apr-Jun were significantly greater than Ex-N observed during Oct-Dec but lower than Ex-N in Jan-Mar and Ex-N in Jul-Sept ($p < 0.05$). Measured Ex-N in J.B. Foltz ditch was high during Jul-Sept, and Jan-Mar ($p < 0.0001$). It was quite difficult to compare these data with other Ex-N data published on Indiana drainage ditches due to the lack of data availability. The findings of high values in this study were not surprising because agricultural drainage ditches have been reported to carry high concentration levels of nitrogen (David et al., 1997; Gentry et al., 1998; 2000; Smith et al., 2008). Seasonal variations were also observed in Marshall ditch where Ex-N during Jul- Sept was significantly lower than Ex-N during Oct-Dec ($p < 0.005$) and lower than Apr-Jun Ex-N ($p < 0.02$). Sampling location (upstream and downstream from tile drain) tested across seasons resulted in no significant variation in mean Ex-N concentrations within all three sites; however mean Ex-N concentrations during Jul-Sept were significantly lower upstream than downstream of tile drains ($p < 0.05$) in Box ditch.

CONCLUSIONS

Results from this study suggested that sediments play an active role in controlling water column P concentrations. EPC_0 measurements indicated that sediments in these ditches acted as temporary sinks or sources for P. Sediment Ex-P was generally higher in Box ditch, followed by J.B. Foltz ditch and Marshall ditch. Overall, mean Ex-P concentrations were high during October through December at all three sites. Analysis of PSI values showed that sediment sorption ability in J.B. Foltz ditch was higher than that of sediments in the other two ditches for all seasons. Ex-N concentrations showed that J.B. Foltz ditch had the highest Ex-N with highest values in this ditch observed during Jul-Sept.

Sediments in tile-fed drainage ditches did not appear to be sensitive to inputs from tile drains with respect to in-stream nutrient cycling parameters. This can be explained by the fact that these ecosystems are continuous systems, part of hydrological network, and in-stream transport processes involve the entire ditch environment from upstream to downstream as a whole. This lack of sensitivity also suggested that agricultural drainage ditches in the Upper Midwest states influenced considerably the quality of downstream waters. However, more investigations must be conducted on sediment insensitivity to tile drain inputs at different reach scale and different ditches (vegetated, non-vegetated, dredged, and non-dredged). Data from this study indicated that drainage ditches behaved as natural systems by acting as sinks or sources of nutrients they receive. Nutrient uptake by benthic sediments in drainage ditches is not always efficient, therefore proper drainage system management options should be implemented to optimize for nutrient removal from the water column while maintaining adequate drainage.

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